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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

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UNSTABLE RESONATOR RETROFITTED HANDHELD LASER DESIGNATOR

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Night Vision & Electro-Optics Laboratory

June 1978

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A confocal, unstable resonant cavity and hybrid system was retrofitted to an existing "Handheld Laser Designator" (HLD). Performance characteristics of the retrofitted laser with a conventional version are compared. Unique capabilities of the unstable resonator are described, and recommendations for future development based on test results and experimentation are included.

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HANDHELD LASER DESIGNATOR

1. INTRODUCTION AND BACKGROUND

The objective of this program was to investigate the characteristics of a confocal, unstable resonator design installed in an actual, fieldable laser designator. An existing "Handheld Laser Designator" (HLD), manufactured by Hughes Aircraft, was retrofitted with a negative-branch unstable resonator laser and hybrid pump cavity in place of the conventional plane-mirror/porro prism resonator and gas-cooled pump system.

The rationale for this course of action was to determine if the improvement in operating characteristics of this form of resonator, shown to be promising in previous laboratory-environment studies, could be realized in a packaged configuration. Secondly, it was expected that this retrofitting would reveal design shortcomings in the prototype configuration, so that future development would benefit from experience and provide a valuable technological basis.

In addition to the retrofitted resonator cavity, a new type of (Hughes Aircraft proprietary) laser pumping head was incorporated. In this new, "hybrid" system, only the laser crystal is liquid cooled. The flashlamp is conduction cooled to a separate heat sink. The crystal is surrounded by a transparent jacket through which a relatively small volume of liquid is circulated. Both the jacketed crystal and the flashlamp are within a reflective pumping cavity. The advantages of this system are: (1) Long lifetime due to efficient liquid cooling but with a relatively small volume of liquid. (b) Since the liquid is not in contact with either the reflective pump cavity or the flashlamp, it cannot produce deterioration of these components. (c) The water-jacket material can be easily fabricated from uv absorbing material, thus reducing solarization effects in the laser crystal.

2. OPTICAL DESIGN

The optical layout is schematically shown in Figure 1. The folding prisms were necessary for packaging the optical components within the available space of the retrofitted HLD configuration. The "raw" laser beam is directed by prism B to an expanding telescope, shared with the viewing system of the designator. The actual, unfolded resonator length is approximately 42.5 cm, and the resonator optical magnification is $m = 2$. In the geometric optics approximation, the magnification is defined by the ratio of the focal lengths of M1 and M2 ($m = f1/f2$). The output coupling fraction is given by the relation $(1 - 1/m^2)$.

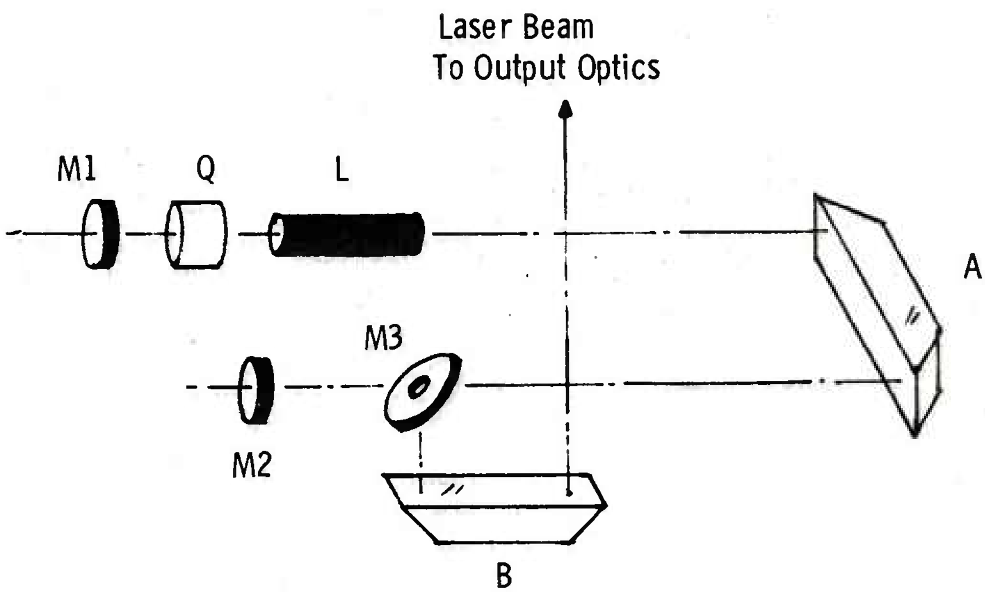

Figure 1. Schematic diagram of the optical component layout of the retrofitted unstable resonator laser module.

Since this relation is based on uniform profile internal radiation, it gives high values for real systems. However, it provides a guide by which the effect on output coupling by m-variation can be estimated.

A simplified schematic of the laser optical system is shown in Figure 2. The labelled components correspond to those of Figure 1. Operation of the Q-switch is similar to that of conventional laser systems. After an inversion is pumped in the laser rod, the Q-switch is "opened" and laser oscillation is initiated in an oscillating axial "core," with radial dimension somewhat smaller than that of the laser rod. Because of the optical magnification of the unequal focal length mirrors M1 and M2, internal flux is radially magnified with each pass, and amplified in the outer region of the laser rod. This radial magnification increases until the internal mode reaches a radial dimension greater than the aperture in the output mirror, and hence is coupled out of the resonator. Thus, the characteristic diffraction-coupled output of an unstable resonator appears as an annulus in the near field. The annular near-field beam transforms to a Fraunhofer pattern in the far-field, similar to the well known Airy pattern produced by a truncated plane-wave. Preliminary experiments[1,2] have shown that near diffraction-limited performance can be expected. In essence, the unstable resonator laser dynamic operation can be viewed as that of an oscillator-amplifier in an integral unit.

3. ELECTRONICS DESIGN

A series injection trigger-transformer is required for flashlamp ignition with the conductively cooled flashlamp. The transformer design combines the trigger and PFN inductor into a single unit and replaces the existing HLD inductor. In addition, a simmer power supply has been added which is used to generate the flashlamp keep-alive current. This supply consists of a constant current switching regulator driving a DC to DC converter. The simmer supply generates an open circuit voltage of approximately 500 V and when connected to a load, becomes a 100 milliampere constant current supply.

4. PACKAGING/MECHANICAL DESIGN

To package the unstable resonator and the hybrid cooling components within the approximate shape factor of the existing HLD, a new optical bench assembly was required. The bench

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1. T. F. Ewanizky and J.M. Craig, "Negative-Branch Unstable Resonator Nd:YAG Laser," Applied Optics, Vol. 15, pp 1465-1469, June 1976.

2. T. F. Ewanizky, "An Unstable-Resonator Flashlamp-Pumped Dye Laser," Applied Physics Letters, Vol. 25, pp 295-297, Sept 1974.

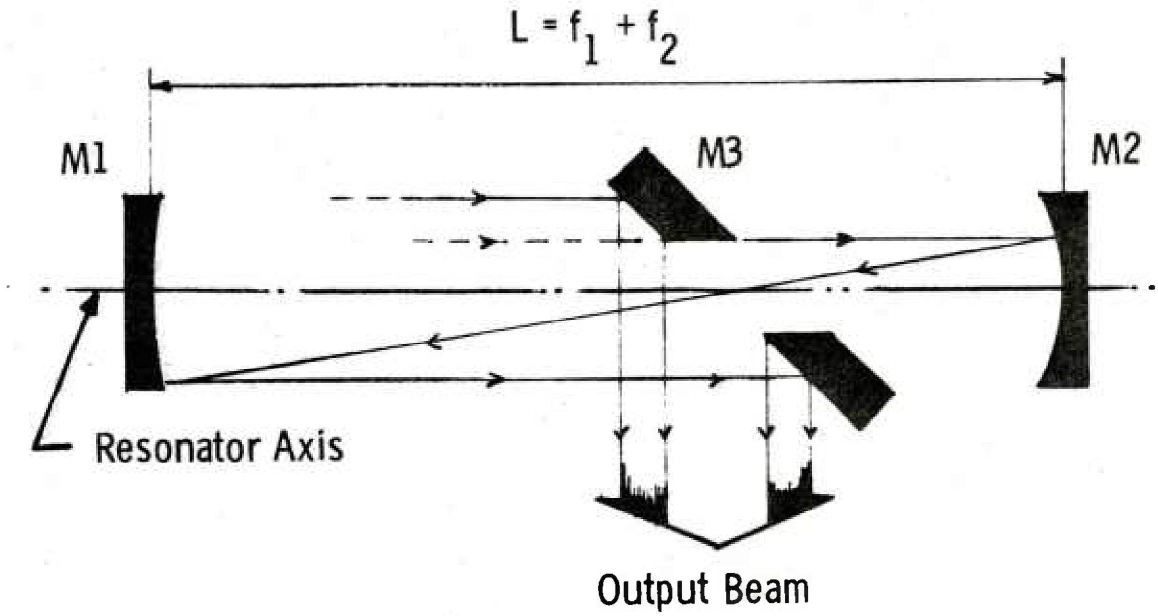

Figure 2. Negative-branch unstable resonator.

provides the structural mounts for the resonator optics, laser pump cavity, and the beam expander/visual optics assembly. In the new design the resonator cavity is environmentally sealed with a cover that permits this volume to be purged with dry nitrogen. Flashlamp module removal has been kept simple and is performed by loosening several screws. The resonator cavity remains sealed while changing lamp assemblies.

The flashlamp and laser rod use the hybrid cooling technique. The lamp is pressed into a layer of barium sulfate that conducts the flashlamp heat load into an aluminum fin array. The laser rod is surrounded by a glass sleeve, and an ethylene glycol-water mixture is circulated past the rod. The rod heat load is removed via a separate liquid to air-heat exchanger. The two heat exchangers are located parallel to each other below the optical bench. A squirrel cage blower and motor, similar in size to the unit used in the original HLD design, pulls outside cooling air through the electronics section cold plate and heat exchangers. The fan motor shaft is double-ended and is used to power a miniature centrifugal pump that circulates the liquid coolant past the rod.

The overall unit weight is approximately the same as the original HLD.

5. INITIAL PERFORMANCE TESTING

The laser head was constructed in modular form, and performance tests on "raw" beam output were performed before installation in the designator housing. (The test data presented in this section were obtained by contractor personnel and excerpted from a progress report.)

Figure 3 shows an input-output energy curve for the M = 2 unstable resonator. Note that there is virtually no dependence of efficiency on pulse repetition frequency (PRF). Beam divergence was determined by measuring the energy fraction transmitted through apertures placed in the focal plane of a 1 meter lens.

Figure 4(a) shows an "energy-in-the-bucket" measurement on the M = 2 cavity with the length optimized at 16 pps, 8.4 joules input and 90 millijoules output. These results are comparable to those reported in the T. F. Ewanizky and J.M. Craig paper.[1] The results shown are approximately 30-50% greater than theoretical calculations for a uniformly illuminated aperture. The difference probably arises from the fact that the actual amplitude and phase distributions at the output-coupler mirror are not uniform.

The effects of mirror misalignment on divergence, efficiency, and output beam direction (beam steering) are shown in Figures 5 and 6. These data were taken at 10 pps, with the cavity length optimized at that PRF, by successively tilting

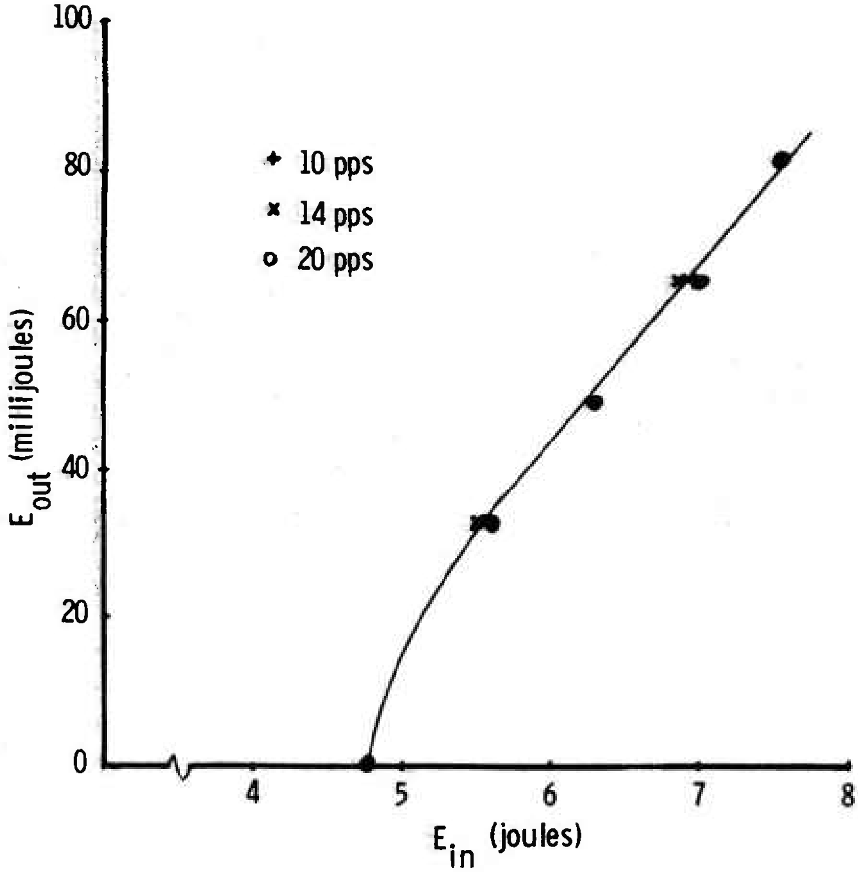

Figure 3. Input-output energy characteristics for the M = 2 unstable resonator.

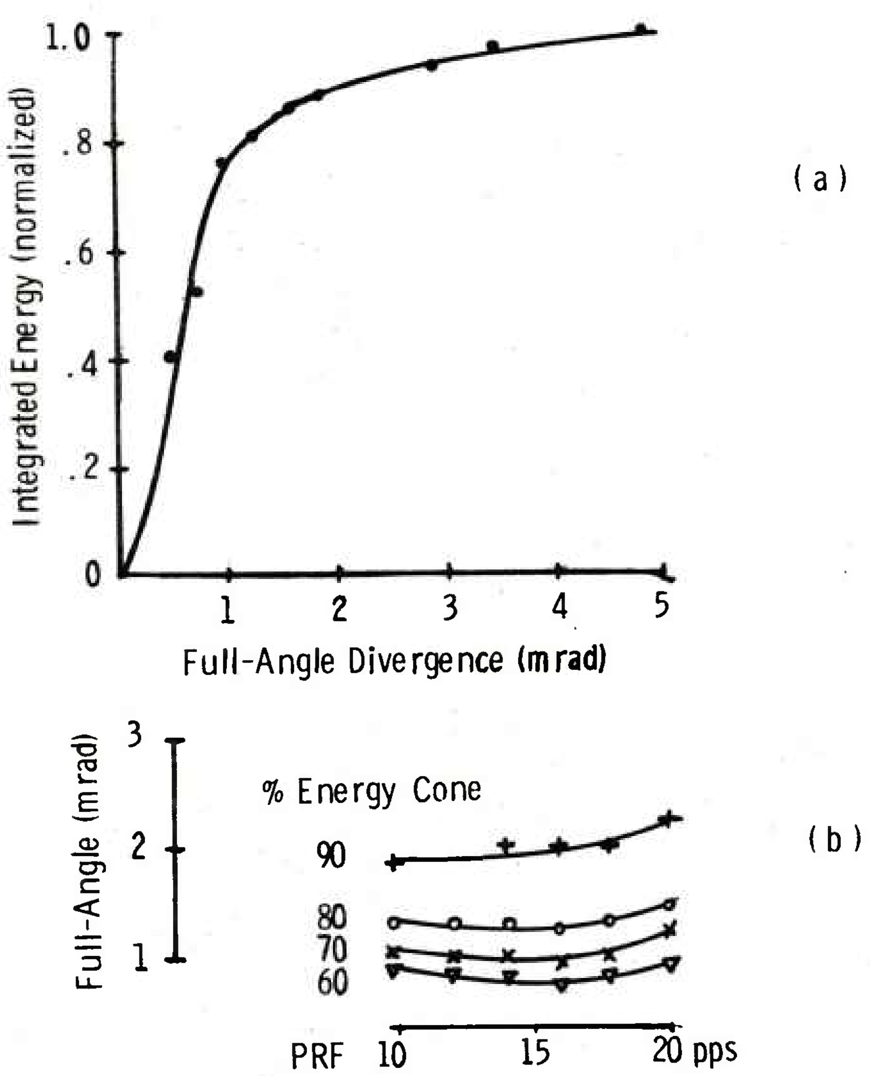

Figure 4. M = 3 unstable resonator, 90 mJ output energy per pulse. (a) Beam divergence 16 pps, (b) Divergence vs. PRF.

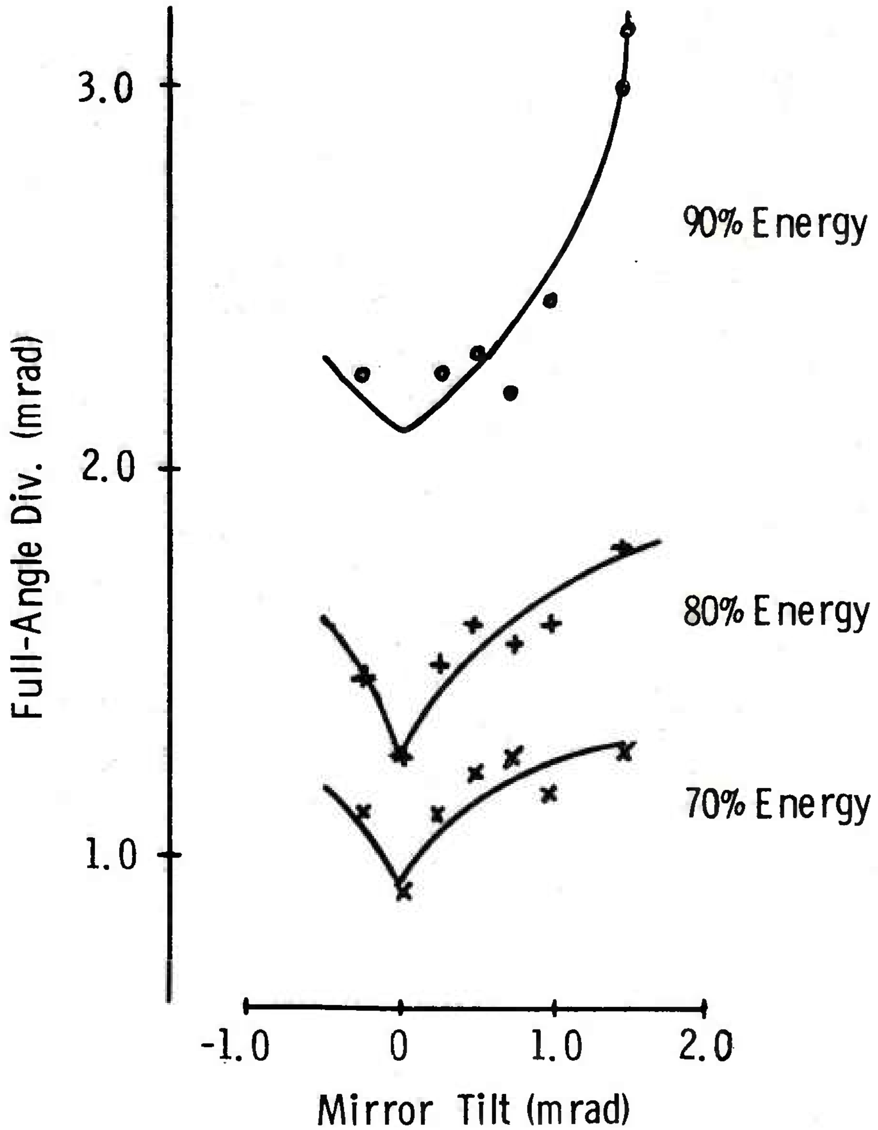

Figure 5. Divergence vs. mirror tilt for M = 2 unstable resonator.

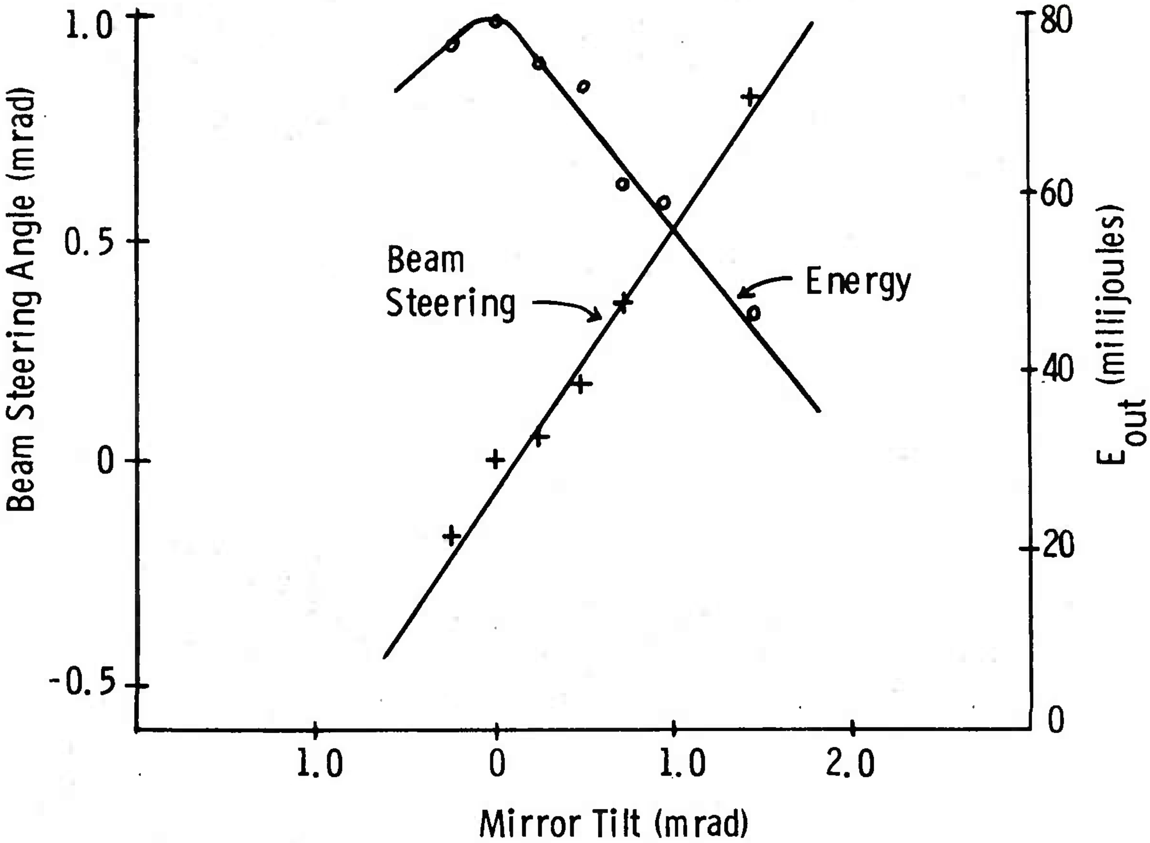

Figure 6. Energy, beam steering vs. mirror tilt
M = 2 unstable resonator, 10 pps.

the short focal length mirror. A 100 microradian tilt of the mirror increased the divergence by only 10%, and a 200 microradian tilt decreased the output energy by only 5%. The measurements indicate that the output beam direction changes 0.6 mrad for a 1 mrad tilt of the mirror, in close agreement with value of $2/(M + 1)$ mrad per mrad tilt, based on simple geometric calculations.

The tilt and longitudinal position of the output-coupler mirror had little effect on the laser output. Tilting the mirror $\pm$ 20 mrad had no noticeable effect on efficiency, although the beam steering was significant (in principle, twice the tilt angle of the mirror). Rotations of 10-20 mrad about an axis normal to the mirror face resulted in only a 5% drop in output energy. Longitudinally translating the mirror as much as 3.5 cm from the intracavity focus had no noticeable effect on either efficiency or divergence.

A comparison of the unstable resonator performance with a conventional resonator was performed based on using a plane-parallel cavity consisting of a 47% reflectivity output coupler, porro-prism reflector, and the same $LiNbO_3$ crystal, flashlamp laser rod and pump cavity used in the unstable resonator. The 48 cm resonator length was the same as that of the M = 2 unstable resonator.

During these measurements, it was found that the best divergence results were obtained using quartz wedges in the Pockels cell, since quartz takes a much better surface finish than the relatively soft calcite. However, in the unstable resonator, quartz wedges of practical dimensions provide insufficient angular separation of the two polarizations to provide adequate laser hold-off necessary for Q-switched operation. In the comparison, data were taken at 1 pps, with the unstable resonator cavity length optimized at the PRF. For higher PRFs an 11.4 meter focal length negative lens was mounted in the conventional resonator, and the unstable resonator cavity length was decreased to compensate for the thermal lensing and to optimize laser performance between 10 and 20 pps.

Figure 7 shows the input-output energy characteristics of the two resonators at 1 pps, and Figure 8 shows the dependence vs PRF for the conventional resonator. Under the necessarily dissimilar operating conditions outlined above, it is seen that the conventional resonator is more efficient than the unstable resonator. However, it is also more sensitive to thermal lensing changes arising from the changes in PRF, as can be seen by comparing Figure 8 to Figure 3, where there is no indication of dependence on PRF.

Figure 9 shows smoothed curves representing "energy-in-the-bucket" measurements on the two resonators at 1 pps and 90 millijoules output energy. The solid curve represents the

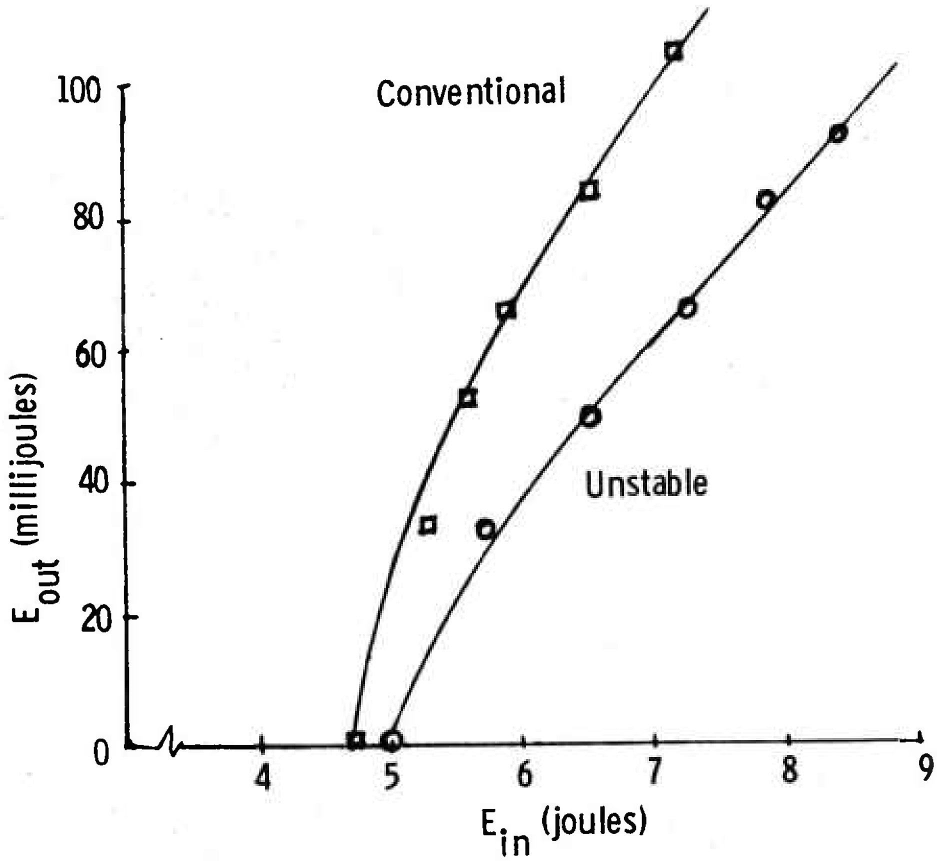

Figure 7. Input-output energy characteristics, 1 pps, of conventional and M = 2 unstable resonator.

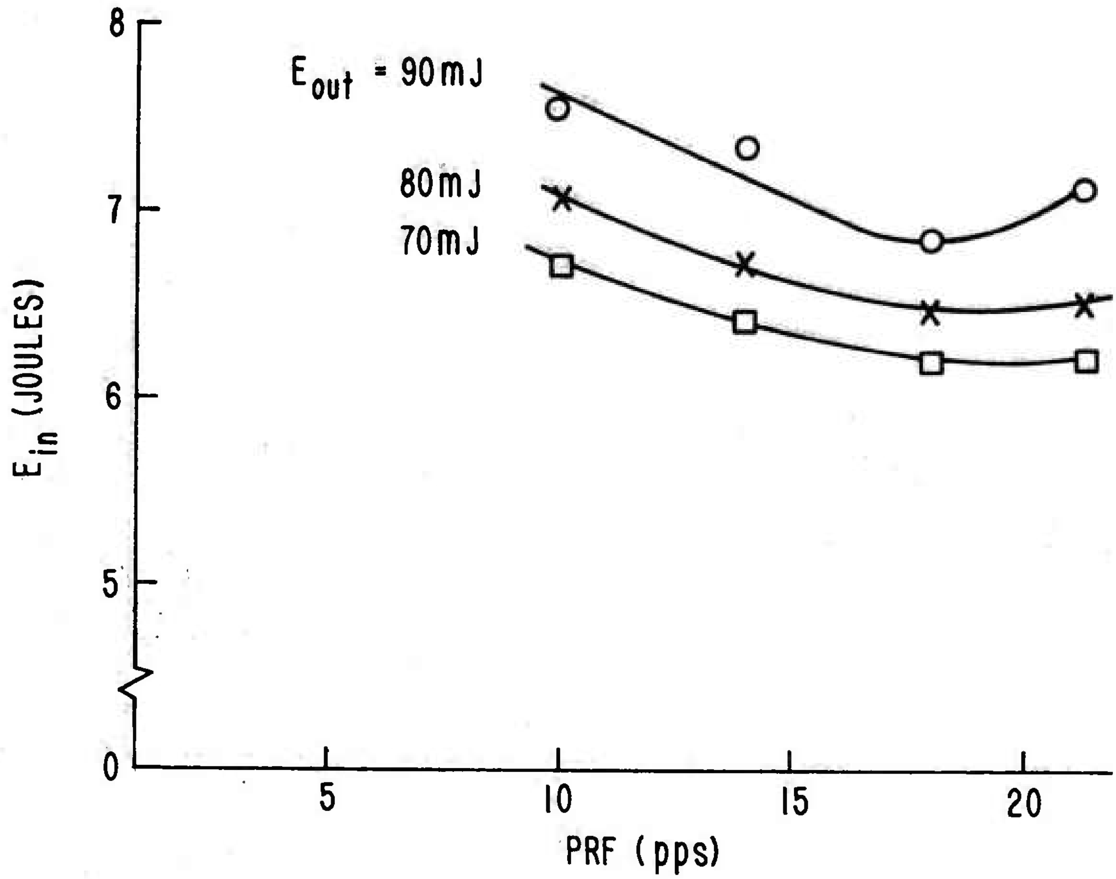

Figure 8. E_{in} vs. PRF. Conventional resonator with 11.4 meter negative compensating lens.

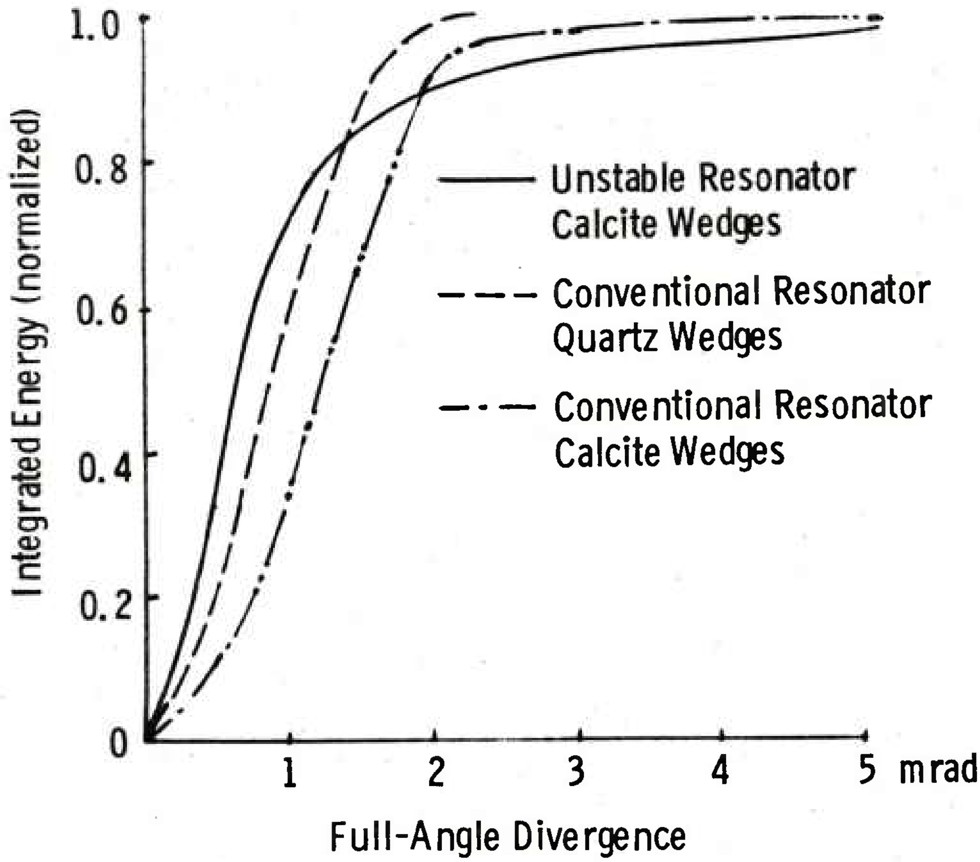

Figure 9. Divergence. Conventional resonator and M = 2 unstable resonator, 1 pps, 90 mJ output.

conventional resonator with quartz wedges in the Pockels cell, and the dotted curve represents the conventional resonator with calcite wedges. Although the unstable resonator has a larger 90% energy cone, it also has a higher brightness than the conventional resonator.

Variation of far-field divergence with PRF at 90 millijoules output energy is shown in Figure 10 for the unstable resonator (same as Figure 4(b)) and the conventional resonator with quartz wedges. Note that in each case the divergence is reduced to the respective 1 pps value in Figure 9 at a PRF between 10 and 20 pps implying that Figure 9 also applies at these higher PRFs. These curves show that the unstable resonator is considerably less dependent on thermal lensing effects than the conventional resonator.

The unstable resonator annular far-field intensity pattern is spread out more than that of a circular aperture having the same outer diameter. Published calculations of the far-field intensity distribution arising from such an annulus are plotted in Figure 11. Although the side lobes are larger than in the case of a fully illuminated circular aperture, the angular width of the central maximum can be significantly less. This is the basis for the claim that the unstable resonator has high brightness in the far-field. The unstable resonator side lobes were quantitatively assessed by using a microdensitometer to scan the far-field intensity pattern recorded on 35 mm infrared film. The film showed the characteristic diffraction structure near the center of the pattern, but outside the angular width of the 90% energy cone the intensity gradually decreased in a more or less uniform way. By comparing exposures having different amounts of attenuation, it was determined that the intensity just outside the 90% energy cone is approximately 27 dB less than the peak value.

6. PERFORMANCE EVALUATION OF COMPLETED, RETROFITTED DESIGNATOR

The completed, retrofitted unstable-resonator designator was essentially unchanged in physical appearance from the standard HLD. The raw beam from the laser module (diagrammed in Figure 1) is directed through a pair of optical wedges for boresighting adjustments, then to an HLD telescope assembly. The telescope is nominally 6-power magnification, so that the output beam appears as an expanded annulus with approximately 2 cm inner and 3.5 cm outer diameters.

The resonator system was adjusted, during designator fabrication, to give optimum results at 10 pps. Laboratory testing was conducted at this repetition rate and the following results were obtained: (a) The output beam appeared to be a symmetrical, approximately uniformly illuminated annulus. (b) Shot-to-shot reproducibility was good, with no more than $\pm$ 1% amplitude jitter. This factor reflects the combined operation of both the laser and the pumping system. (c) Far-field beam impact point appeared to be 1.1 mrad high with

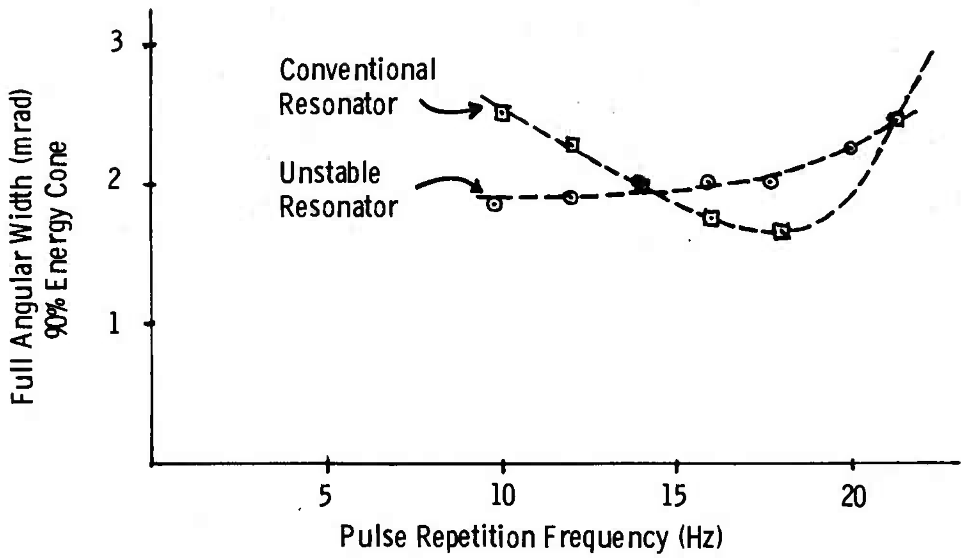

Figure 10. Divergence vs. pulse repetition frequency. Unstable resonator (M = 2), compared with conventional resonator using compensating lens to reduce thermal lensing effect.

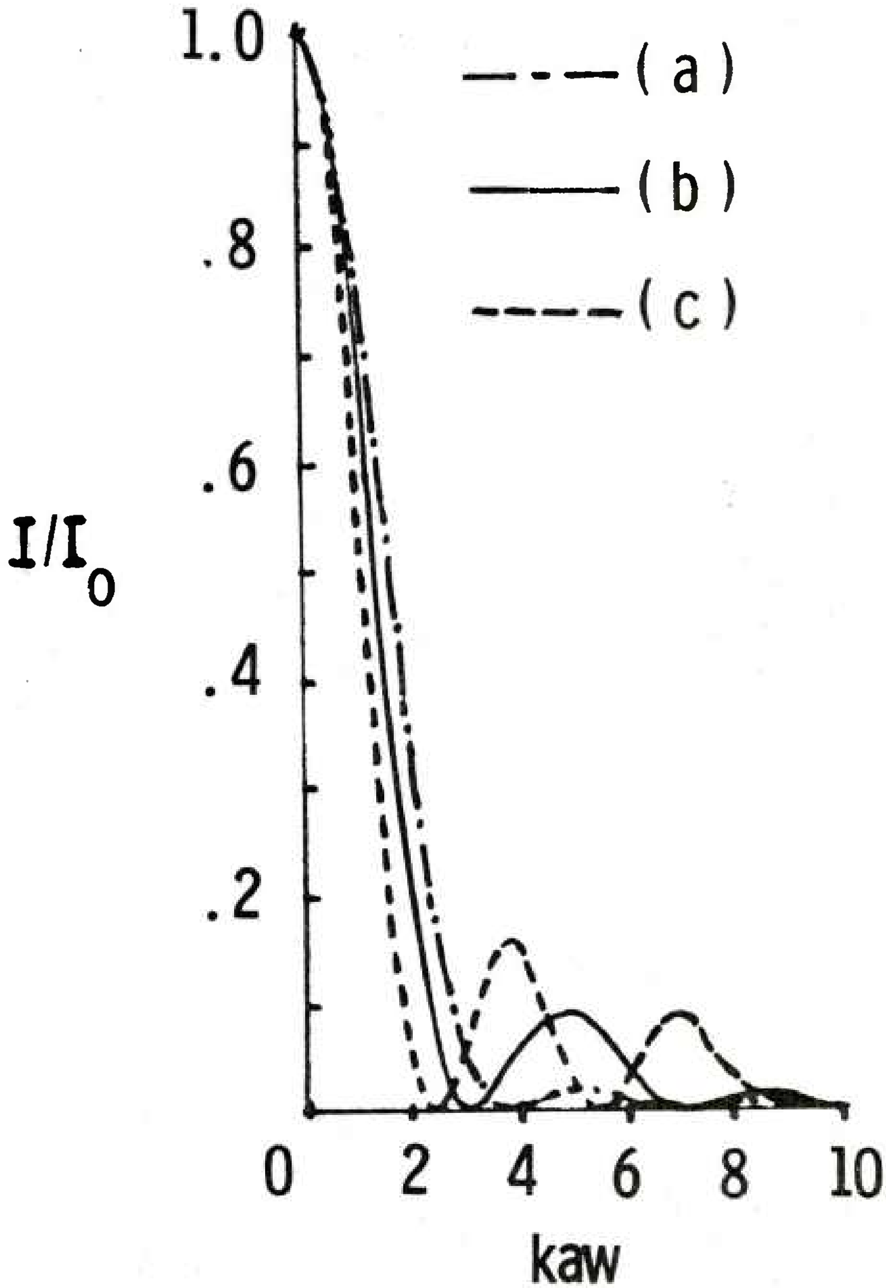

Figure 11. Normalized intensity curves for Fraunhofer patterns of (a) circular aperture, (b) annular aperture with M = 2, and (c) annular aperture with M 1. k is the laser wave vector, a is the outer radius of the aperture, and w is the angular coordinate of the far-field point (Ref. M. Born and E. Wolf, Principles of Optics, Pergamon, Oxford, 1975, p. 416).

respect to aiming point. (d) Beam wander of 0.15 mrad or less was found to occur within the first few (approximately 2) seconds of operation from a "cold" condition. After this period, no significant change in far-field impact point occurred over a continuous operation time of a few minutes. (e) Near-field output energy was measured to be 60 mJ per pulse at 10 pps. (f) Pulse duration was measured to be 13-14 nanoseconds (full-width, half-maximum), with a nearly symmetrical temporal shape. (g) Beam divergence measurements were made by measuring the relative energy passing through various diameter apertures placed at the focal-plane of a well corrected lens. The full-angle beam divergence was 0.6 to 0.7 mrad for 90% of the emitted energy with greater than 75% energy within 0.5 mrad.

The same measurements were conducted with a standard HLD designator, using a conventional resonator and pump cavity, in order to establish a performance comparison. Table 1 shows the result of the comparison measurements.

Table 1. Performance comparison of standard HLD designator with retrofitted unstable resonator/hybrid pump cavity version.

	HLD	Unstable Resonator
Energy/pulse (mJ)	58	60
Pulse duration (FWHM) (ns)	22	14
Peak Power (MW)	2.6	4.3
Full-Angle Beam Divergence (mrad)		
50% energy	0.39	0.37
75% energy	0.58	0.48
90% energy	0.82	0.65
Shot-to-shot Amplitude Stability (%)	± 10	± 1

7. DISCUSSION OF RESULTS AND CONCLUSION

The retrofitted unit demonstrated good performance which was within the target specifications initially proposed by the contractor. Comparison with the standard HLD unit shows that the unstable resonator system equals or exceeds its performance

in a number of catagories. This comparison highlights the inherent qualities of the unstable resonator for designator application.

The retrofitted unit was, in fact, handicapped because the new laser module design constraints were imposed by the HLD configuration and output optics. A second-generation effort for an unstable-resonator designator would benefit by consideration of the results obtained with the retrofitted version.

(a) From the test data, it is seen that the beam divergence of the completed unit, using the collimating telescope, was greater than expected, compared to values of "raw" beam divergence made with the laser module. The raw beam divergence was 2 mrad or less at 90% energy. After collimation by the six power HLD telescope, the divergence angle was only reduced to 0.6 to 0.7 mrad. The apparent reason for this is that the annular output beam of the unstable resonator contains most of its energy in the outer region of the telescope optics, and thus suffers from lens aberrations to a greater extent than, say, a gaussian beam whose maximum intensity is relatively centralized.

(b) A significant source of beam degradation also existed in the laser resonator optics, in the relatively poor quality of fabrication of the angled output (scraper) mirror. The aperture in this mirror had a visibly rough edge, which is known to be a strong factor in beam quality degradation in unstable resonators. The cause for this problem was simply a lack of experience in fabrication.

(c) In the retrofitted laser module, the length of the resonator was fixed by physical constraints, and optimized to produce best output collimation at some fixed repetition rate. No corrective optics to reduce the "lensing" effect of the laser rod was used. This effect is proportional to the pulse repetition rate and input pumping energy and consequent temperature of the laser rod. With increasing temperature due to increase in repetition rate, the laser rod acts as a positive lens with decreasing focal length. The net effect is to make the effective length of the resonator too short. Since the confocal resonator acts as an expanding telescope in coupling internal radiation out of the laser, the output beam diverges. However, this can be simply compensated for by shortening the resonator length. This could be accomplished, mechanically, by setting the position of one end mirror as a function of repetition rate setting. Thus, performance would automatically be optimized at any repetition rate, without resort to complex optical compensation techniques necessary for conventional resonators. From laboratory experience with these systems, it

is believed that their inherent insensitivity to misalignment makes this simple approach feasible.

(d) Although extensive quantitative testing was not done in this area, it was found that the latitude of insensitivity of laser operation to repetition-rate was not as great in the packaged unit as it was in the data of the "bare" module previously presented. Evidently, a different thermal environment is present in the laser module when it is packaged in the designator housing. This is probably a consequence of the difference in cooling systems between the standard and retrofitted designator.

8. RECOMMENDATIONS

From the previous sections, it can be concluded that an extended effort to achieve improved designator performance through the application of unstable resonator technology should concentrate on a design policy specifically guided by that technology. Problem areas were revealed by the retrofitting procedure that was not evident in the experimental phase. Some of these arose because of the constraints imposed by the retrofitting, and some by non-optimum optical fabrication.

A second generation effort should, perhaps, start with a "brassboard" design for only the laser module, itself, in order to achieve the best possible performance and stability from that unit alone. This would include appropriate unstable resonator optics, Q-switch, and an efficient pumping cavity, but in a configuration suitable for packaging.

The next logical phase would be the design of a packaged version, where the effort would concentrate on mechanical design that would result in a stable optical "bench," appropriate for installation in a complete designator configuration. This phase would, perhaps, be the most critical, since ultimate performance of the designator system will be highly dependent on its design. That is, if this interface between the laser module and the output optics of the designator is faulty, the total system performance will be degraded.

Furthermore, it is in this phase of designing the laser optical bench that provisions for mirror alignment (for thermal compensation) would be devised. Finally, the exit optics of the designator, the telescope, should be designed so that aberration is minimized for an annular beam.

In general, all the conclusions and recommendations can be summarized by a design policy that is specifically oriented to take advantage of the particular characteristics of the unstable resonator.